

Gauge Mediation Models with Adjoint Messengers

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Abstract

We present a class of models in the framework of gauge mediation supersymmetry breaking where the messenger fields transform in the adjoint representation of the Standard Model gauge symmetry. To avoid unacceptably light right-handed sleptons in the spectrum we introduce a non-zero $U(1)_{B-L}$ D-term. This leads to an additional contribution to the soft supersymmetry breaking mass terms which makes the right-handed slepton masses compatible with the current experimental bounds. We show that in this framework the observed 125 GeV Higgs boson mass can be accommodated with the sleptons accessible at the LHC, while the squarks and gluinos lie in the multi-TeV range. We also discuss the issue of the fine-tuning and show that the desired relic dark matter abundance can also be accommodated.

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1 Introduction

Models with gauge mediated supersymmetry breaking (GMSB) provide a compelling resolution to the supersymmetry (SUSY) flavor problem since the soft SUSY breaking (SSB) terms are generated by the flavor blind gauge interactions [1, 2, 3]. In general, the trilinear SSB A-terms in GMSB scenarios are relatively small at the messenger scale, even if an additional sector is added to generate the $\mu/B\mu$ terms [4]. Because of the small A-terms, accommodating the light CP-even Higgs boson mass around 125 GeV requires a stop mass in the multi-TeV range [5]. On the other hand, a multi-TeV top squark has a very strong influence on the sparticle spectrum [5], if we assume that the messenger fields reside in the $SU(5)$ representations such as $5 + \bar{5}$ or $10 + \bar{10}$. This case is called minimal GMSB scenario, since it is the simplest scenario that preserves gauge coupling unification of the minimal supersymmetric standard model (MSSM) and provides non-zero SSB mass terms for all supersymmetric particles. It is often assumed that all messenger fields have a universal mass in this simplest model. Even if one assumes a large mass splitting among the colored and non-colored messenger fields, the sparticle mass spectrum cannot be entirely separated, since all fields from $5 + \bar{5}$ (or $10 + \bar{10}$) representation have non-zero hypercharge, and they can generate non-zero masses through hypercharge interactions. This means that in these models the maximal splitting among sfermion SSB mass terms cannot exceed the ratio of corresponding fermion hypercharges. Therefore, the colored and non colored sparticle mass spectra are closely linked here. For instance, if we have a multi-TeV mass top squark in the minimal GMSB scenario, then the whole SUSY sparticle spectrum is also around the TeV scale [5]. Note that t - b - τ Yukawa coupling unification can be realized in these models and it provides a specific spectrum for sparticle masses [6].

Sometime ago it was proposed [7] that the messenger fields should reside in the adjoint representations of $SU(3)_C \times SU(2)_L$, namely in $[(8, 1) + (1, 3)]$. In this scenario the colored and non-colored sparticle mass spectra can be significantly separated from each other since these multiplets do not carry hypercharge, and so there is no common contribution to SSB mass terms from $U(1)_Y$ interaction. In this case we can have multi-TeV stop masses, while the sleptons potentially can be much lighter $\gtrsim O(100)$ GeV. Unfortunately, in this scenario the right-handed sleptons and bino do not obtain their SSB mass terms at the same loop level as other particles do, the reason being that the right-handed sleptons and bino do not transform under $SU(3)_C \times SU(2)_L$ and the messenger fields in $[(8, 1) + (1, 3)]$ do not have hypercharge. This is in disagreement, potentially, with the experimental lower bound of 100 GeV on the charged slepton masses [8]. In order to generate a mass for right-handed sleptons of $O(100)$ GeV through renormalization group equation (RGE) running, the some other appropriate sparticle masses need to be in the multi-TeV range. To solve this problem, an additional source which contributes to the SSB mass terms can be proposed. For instance, a messenger field from $(5 + \bar{5})$ can be included [7], in addition to those in $[(8, 1) + (1, 3)]$. Another proposal is for the bino mass to be generated through the gravitational interactions [9]. The bino mass is effective in generating a SSB mass term for the right-handed slepton through RGE running [10], and it was simply assumed that a universal SSB mass term [11] be added to the sparticle masses generated from $[(8, 1) + (1, 3)]$ messenger fields, when the bino is very light.

In general, D-term contribution to the scalar masses can arise whenever a gauge symmetry is spontaneously broken with reduction of rank [12]. Here we propose a scenario where all MSSM sfermions obtain additional SSB mass terms from a non-zero $U(1)_{B-L}$ D-

term [13]. $U(1)_{B-L}$ [14] is one of the most natural extensions of the SM gauge symmetry, and it is also part of $SO(10)$ grand unified theory [15] or Pati-Salam model [16], which are considered to be compelling extensions of the SM. In our scenario, the right-handed sleptons obtain their masses only from the $U(1)_{B-L}$ D -term contribution. The bino mass vanishes at the messenger scale and is generated at low scale through RGE evolution. As we will show, in our scenario the bino mass can lie in the $O(\text{GeV})$ – $O(100 \text{ GeV})$ interval.

It has been shown in Ref. [17] that non-universal gaugino masses at the GUT scale (M_{GUT}) can help resolve the little hierarchy problem in gravity mediated scenario [18]. In particular, the little hierarchy problem can be resolved if the ratio between $SU(2)_L$ and $SU(3)_c$ gaugino masses satisfies the asymptotic relation $M_2/M_3 \approx 3$ [17]. In this case the leading contributions to $m_{H_u}^2$ through RGE evolution are proportional to M_2 and M_3 and can cancel each other. This allows for large values of M_2 and M_3 in the gravity mediated supersymmetry breaking scenario [18], while keeping the value of $m_{H_u}^2$ relatively small. On the other hand, large values of M_2 and M_3 yield a heavy top squark ($> \text{TeV}$), which is necessary to accommodate $m_h \simeq 125 \text{ GeV}$. A similar observation was made in GMSB scenario with non-universal gaugino masses at the messenger scale [19]. We also obtain in our scenario a relatively light MSSM μ -term which helps ameliorate the little hierarchy problem at the electroweak scale (M_{EW}) [20].

The remainder of this paper is organized as follows: We present the model in Section 2 and in Section 3 we summarize the scanning procedure and the experimental constraints we employ. In Section 4 we present our results focusing on the low mass spectrum for the sleptons and accommodating the 125 GeV Higgs boson mass and relic dark matter abundance. We also provide in this section a table of benchmark points which exemplifies our findings. Our conclusions are discussed in Section 5.

2 Essential Features of the Model

Supersymmetry breaking in a typical GMSB scenario takes place in a hidden sector, and this breaking is transferred to the visible sector via messenger fields. These messenger fields interact with the visible sector via the SM gauge interactions and induce the SSB terms in the MSSM through loops. In order to preserve perturbative gauge coupling unification, the minimal GMSB scenario can include N_5 pairs of $(5 + \bar{5})$ ($N_5 = 1, \dots, 5$) or one $(10 + \bar{10})$ pair, or one combination $10 + \bar{10} + 5 + \bar{5}$, or one pair of $15 + \bar{15}$ of $SU(5)$ multiplets [2]. On the other hand, it was proposed in [7] to have the messenger fields reside in $[(8, 1, 0) + (1, 3, 0)]$ representations of $SU(3)_C \times SU(2)_L \times U(1)_Y$. In this scenario the colored and non-colored sparticle spectra can be significantly separated from each other, the reason being that the messenger fields do not carry hypercharge, and so there is no common contribution to the SSB mass terms from $U(1)_Y$ interaction. This allows one to have relatively light sleptons and electroweak gauginos which can be accessible at the LHC, while the gluino and stop can be in the multi-TeV mass range.

In this paper we will study the scenario in which the fields in $[(8, 1, 0) + (1, 3, 0)]$ are the messengers of SUSY breaking. We also propose an additional contribution to the SSB masses of the sfermions from the D -term associated with $U(1)_{B-L}$ gauge group to avoid inconsistently light right-handed slepton solutions. The bino in our scenario, as we will show, obtains a sizable mass through RGE evolution. In order to incorporate SUSY breaking in the messenger sector, the fields in $[(8, 1, 0)(\Sigma_8) + (1, 3, 0)(\Sigma_3)]$ dimensional

multiplets are coupled, say, with the hidden sector gauge singlet chiral field S [7],

$$W \supset (m_3 + \lambda_3 S) \text{Tr}(\Sigma_3^2) + (m_8 + \lambda_8 S) \text{Tr}(\Sigma_8^2). \quad (1)$$

Here, for simplicity, we assume $M_{\text{Mess}} \equiv m_3 = m_8$, and the F_S component of S has a non-zero vacuum expectation value (VEV). W denotes the appropriate superpotential of the model. Below the messenger scale M_{Mess} , the fields Σ_3 and Σ_8 decouple generating SSB masses for the MSSM fields. The gaugino masses generated at one-loop level are given by

$$M_1 = 0, \quad M_2 \simeq \frac{g_2^2}{16\pi^2} 2\Lambda_3, \quad M_3 \simeq \frac{g_3^2}{16\pi^2} 3\Lambda_8, \quad (2)$$

where $i = 1, 2, 3$, stand for the $U(1)_Y$, $SU(2)_L$, and $SU(3)_c$ sectors, respectively, and $\Lambda_3 = \lambda_3 \langle F_S \rangle / M_{\text{Mess}}$ and $\Lambda_8 = \lambda_8 \langle F_S \rangle / M_{\text{Mess}}$. The bino mass M_1 will be generated at the two-loop level [22], and it vanishes at the messenger scale. As we will show, the RGE evolution with the relevant SUSY parameters results in bino masses of around 100 GeV or so.

The SSB masses for the MSSM scalars induced at two-loop level are as follows [7]

$$\begin{aligned} m_{\tilde{Q}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 3\Lambda_8^2 + \frac{3}{4} g_2^4 2\Lambda_3^2 \right] \\ m_{\tilde{U}}^2 = m_{\tilde{D}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 3\Lambda_8^2 \right] \\ m_L^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{3}{4} g_2^4 2\Lambda_3^2 \right] \\ m_{H_u}^2 = m_{H_d}^2 &= m_L^2 \\ m_E^2 &= 0. \end{aligned} \quad (3)$$

The right-handed slepton masses will be generated at a higher loop level, and thus, they vanish at the messenger scale. However, they are generated below the messenger scale from the RGE evolution. On the other hand, experiments require that the sleptons must be heavier than 100 GeV or so. In order to generate right-handed slepton masses of order 100 GeV or higher in this model, some of the other sparticles should be around 100 TeV or so, which makes supersymmetry much less motivated for solving the gauge hierarchy problem. To avoid this problem we consider an extension of the SM gauge symmetry with $U(1)_{B-L}$. In this case it is natural to assume that the D-term associated with $U(1)_{B-L}$ can provide a non-zero contribution [23] to the scalar SSB mass terms. In summary, the MSSM sfermion masses have the following expression

$$m_{\phi_i}^2 = (m_{\phi_i}^2)_{\text{GMSB}} + e_\eta^2 D^2, \quad (4)$$

where ϕ_i denote the MSSM sfermions, and e_η stands for the sparticle charges under $U(1)_{B-L}$ [14].

The A-terms in our scenario vanish at the messenger scale, which is very common in GMSB models (except when the MSSM and messenger fields are mixed [24], which we do not consider in this study). The A-terms, as usual, are generated from the RGE running and are small compared to the top squark mass. The bilinear SSB term also vanishes at

M_{Mess} , although it is often ignored. We do not impose the relation $B_\mu = 0$, anticipating that the value needed to achieve the electroweak symmetry breaking (EWSB) can be explained by some suitable mechanisms operating at the messenger scale [4].

The sparticle spectrum in our model is therefore completely specified by the following parameters defined at the messenger scale:

$$M_{\text{Mess}}, \Lambda_3, \Lambda_8, \tan\beta, \text{sign}(\mu), N_5, c_{\text{grav}}, D, \quad (5)$$

where M_{Mess} , Λ_8 , and Λ_3 are defined earlier. $\tan\beta$ is the ratio of the VEVs of the two MSSM Higgs doublets. The magnitude of μ , but not its sign, is determined by the radiative electroweak breaking (REWSB) condition. The parameter $c_{\text{grav}} (\geq 1)$ affects the mass of the gravitino and we set it equal to unity from now on. For simplicity, we consider the case $N_5 = 1$. Changing the value of N_5 does not significantly alter the sparticle spectrum [5]. Finally, D denotes the D -term contribution associated with $U(1)_{B-L}$.

Even though the messenger multiplets in this model are incomplete $SU(5)$ multiplets, gauge coupling unification can still be achieved if we assume that the masses of $[(8, 1, 0) + (1, 3, 0)]$ fields are around 10^{13} GeV or so [25]. Note that in this case the gauge coupling unification scale is higher than the conventional SUSY GUT scale $\sim 2 \times 10^{16}$ GeV. In principle, it can be as high as the Planck scale.

3 Scanning Procedure and Experimental Constraints

For our scan over the fundamental parameter space of GMSB with the adjoint messengers, we employed ISAJET 7.84 package [26] supplied with appropriate boundary conditions at M_{Mess} . In this package, the weak-scale values of gauge and Yukawa couplings are evolved from M_Z to M_{Mess} via the MSSM RGEs in the \overline{DR} regularization scheme. For simplicity, we do not include the Dirac neutrino Yukawa coupling in the RGEs, whose contribution is expected to be small.

The SSB terms are induced at the messenger scale and we set them according to Eqs. (2)-(4). From M_{Mess} the SSB parameters, along with the gauge and Yukawa couplings, are evolved down to the weak scale M_Z . In the evolution of Yukawa couplings the SUSY threshold corrections [27] are taken into account at the common scale $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, where $m_{\tilde{t}_L}$ and $m_{\tilde{t}_R}$ are the soft masses of the third generation left and right-handed top squarks respectively.

We have performed random scans over the model parameters given in Eq. (5) in the following range:

$$\begin{aligned} 10^4 &\leq \Lambda_3 \leq 10^6 \text{ GeV} \\ 10^4 &\leq \Lambda_8 \leq 10^6 \text{ GeV} \\ 10^4 &\leq M_{\text{Mess}} \leq 10^{16} \text{ GeV} \\ 0 &\leq D \leq 2000 \text{ GeV} \\ 2 &\leq \tan\beta \leq 60 \\ N_5 &= 1, \quad \mu > 0, \quad c_{\text{grav}} = 1. \end{aligned} \quad (6)$$

Regarding the MSSM parameter μ , its magnitude but not the sign is determined by the radiative electroweak symmetry breaking (REWSB). In our model we set $\text{sign}(\mu) = 1$.

Finally, we employ the current central value for the top mass, $m_t = 173.3$ GeV. Our results are not too sensitive to one or two sigma variation of m_t [28].

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in Ref. [29]. The data points collected all satisfy the requirement of radiative electroweak symmetry breaking (REWSB). We successively apply mass bounds including the Higgs boson [30, 31] and gluino masses [32], and the constraints from the rare decay processes $B_s \rightarrow \mu^+ \mu^-$ [33], $b \rightarrow s\gamma$ [34] and $B_u \rightarrow \tau \nu_\tau$ [35]. The constraints are summarized below in Table 1.

$$\begin{aligned}
123 \text{ GeV} &\leq m_h \leq 127 \text{ GeV} \\
m_{\tilde{g}} &\geq 1.8 \text{ TeV} \\
0.8 \times 10^{-9} &\leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 6.2 \times 10^{-9} \text{ (} 2\sigma \text{)} \\
2.99 \times 10^{-4} &\leq \text{BR}(b \rightarrow s\gamma) \leq 3.87 \times 10^{-4} \text{ (} 2\sigma \text{)} \\
0.15 &\leq \frac{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{MSSM}}}{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{SM}}} \leq 2.41 \text{ (} 3\sigma \text{)} \quad .
\end{aligned}$$

Table 1: Phenomenological constraints implemented in our study.

4 Results

In this section we present the results of the scan over the parameter space listed in Eq. (6). As previously mentioned, the characteristic feature of our model is that all sfermions receive an additional $U(1)_{B-L}$ D -term contribution to their SSB masses, see Eq. (4). Figure 1 represents plots in $M_{\text{Mess}} - \Lambda_3$, $M_{\text{Mess}} - \Lambda_8$, $\Lambda_8 - \Lambda_3$, $M_{\text{Mess}} - \tan \beta$, $\Lambda_8/\Lambda_3 - D$, and $\mu - D$ planes with all points being consistent with REWSB. Green points are consistent with the experimental constraints presented in Table 1. We see from the $M_{\text{Mess}} - \Lambda_3$ plane that M_{Mess} and Λ_3 parameters can lie in a wide range consistent with the current experimental constraints. It is interesting to note that Λ_3 can even be as low as 2×10^4 GeV. On the other hand, from the $M_{\text{Mess}} - \Lambda_8$ plane, Λ_8 is bounded at about 10^5 GeV from below. The $M_{\text{Mess}} - \tan \beta$ panel indicates that there is a slight preference for $\tan \beta > 10$ when $M_{\text{Mess}} < 10^6$ GeV.

The $\Lambda_8 - \Lambda_3$ and $\Lambda_8/\Lambda_3 - D$ planes show that Λ_8 should be larger than Λ_3 over most of the parameter space, even though it is possible to have $\Lambda_8 \leq \Lambda_3$ in a small portion of the parameter space, particularly when $\Lambda_3 > 10^5$ GeV. The D -term contribution to the scalars can be as low as about 100 GeV, which means that experimentally acceptable ($O(100 \text{ GeV})$) slepton masses cannot be generated through RGE evolution if their masses are negligibly small at the messenger scale. Finally, the $\mu - D$ panel shows that the MSSM μ -term as low as 200-300 GeV can be realized. This indicates that in this model the little hierarchy problem is not as severe as in the minimal GMSB scenario with messenger fields allocated in $5 + \bar{5}$ (or $10 + \bar{10}$) representations of $SU(5)$. A more detailed analysis about the little hierarchy problem will be presented when we discuss Figure 3.

Figure 2 displays the mass spectrum with plots in the $m_{\tilde{t}_2} - m_{\tilde{t}_1}$, $m_{\tilde{q}} - m_{\tilde{g}}$, $m_A - \tan \beta$ and $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0}$ planes. The color coding is the same as Figure 1. The colored sparticles are rather heavy as seen from the top panels of Figure 2, but still there is hope that some of them can be tested at the LHC. The stops are required to be heavier than about 4 TeV in order to satisfy the Higgs mass bound. The gluinos and squarks from the first two families (\tilde{q}_L) can be as light as 2 TeV or so. The $m_A - \tan \beta$ plane reveals the correlation between

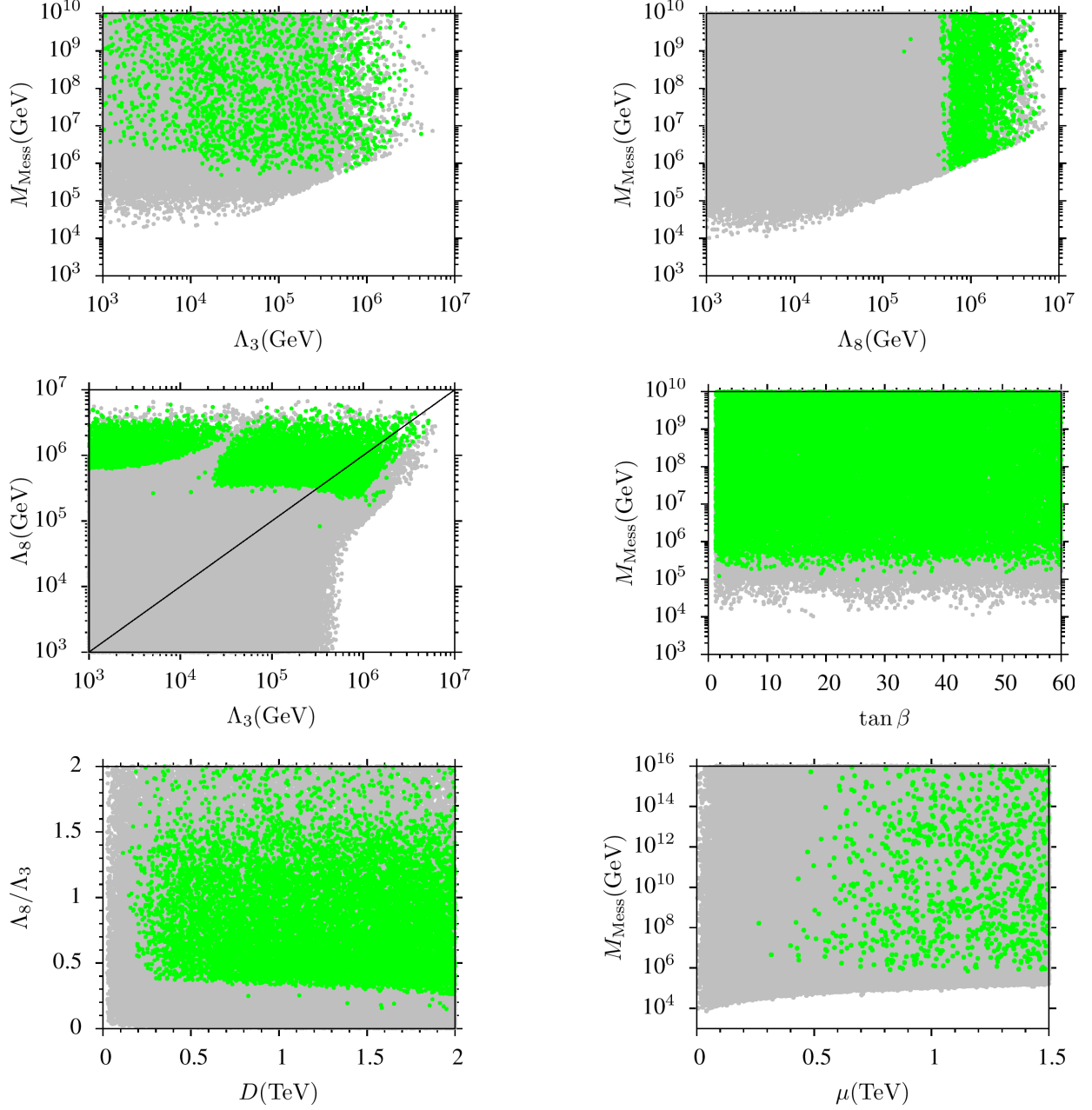


Figure 1: Plots in the $M_{\text{Mess}} - \Lambda_3$, $M_{\text{Mess}} - \Lambda_8$, $M_{\text{Mess}} - \tan \beta$, $\Lambda_8 - \Lambda_3$, $\Lambda_8/\Lambda_3 - D$, and $\mu - D$ planes. All points are consistent with REWSB. Green points are consistent with the experimental constraints in Table 1.

the mass of the CP-odd A -boson and $\tan \beta$. We see that $m_A \sim 1$ TeV is achieved for $\tan \beta \approx 60$. For small and moderate $\tan \beta$ values, m_A is more than 2 TeV and it would be difficult to detect A -boson at the LHC.

Finally the $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0}$ plot shows that in our scenario it is possible to have light sleptons. In particular, we see that the right-handed smuon can be around 200 GeV, which makes it accessible at the LHC. Having such a light smuon in the spectrum can be helpful, in principle, for the muon $g - 2$ anomaly [36]. However, in our scenario the bino mass parameter M_1 has negative values as a result of its RGE evolution, which gives a sizable

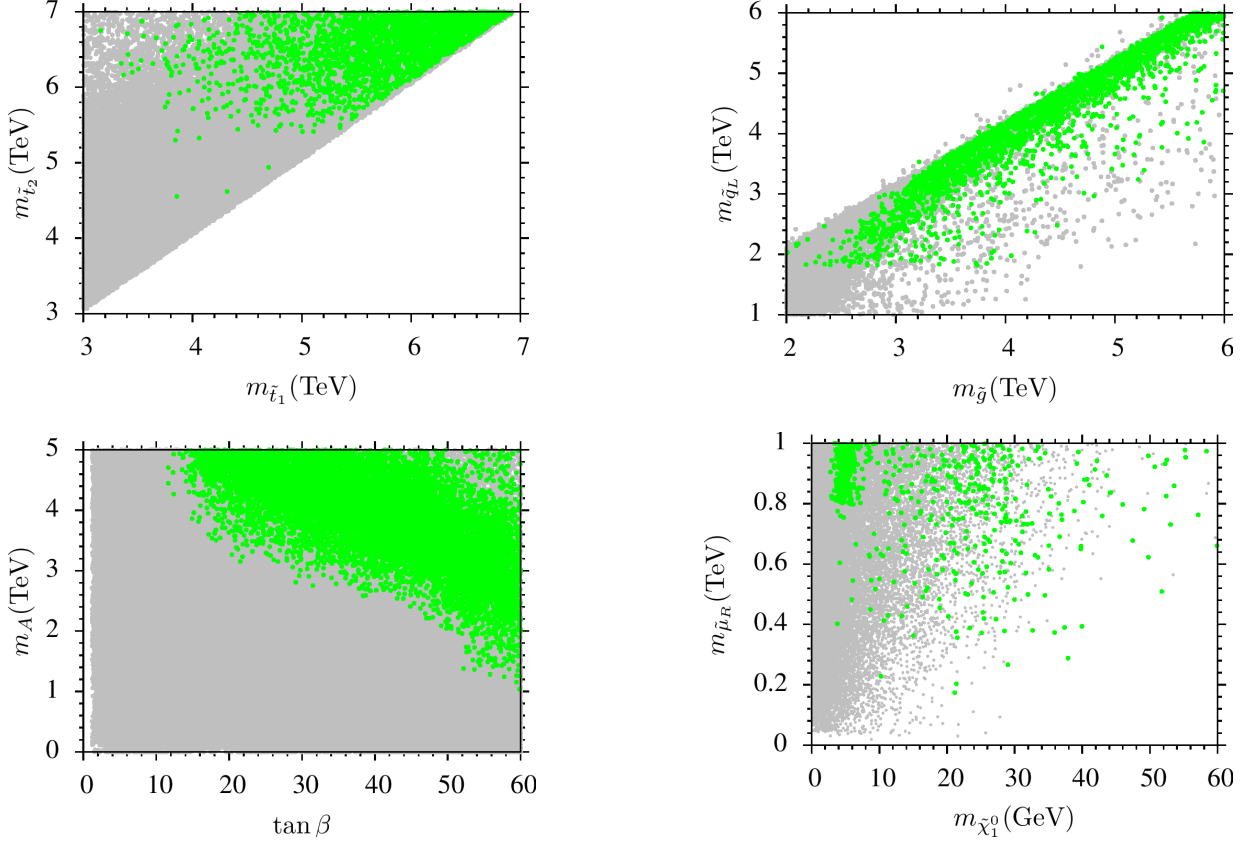


Figure 2: Plots in the $m_{\tilde{t}_2} - m_{\tilde{t}_1}$, $m_A - \tan \beta$, $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\mu}_L} - m_{\tilde{\chi}_1^0}$ planes. The color coding is the same as in Figure 1.

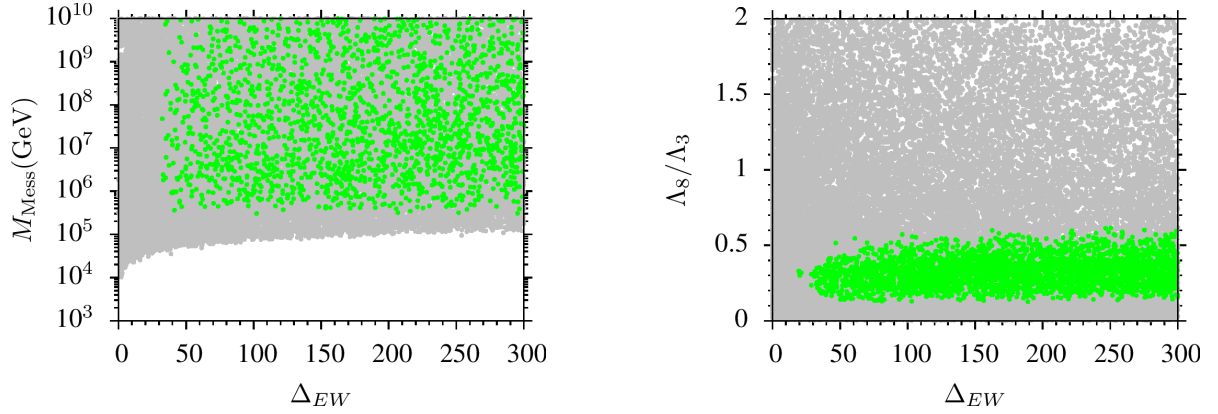


Figure 3: Plots in the $M_{\text{Mess}} - \Delta_{EW}$ and $\Lambda_8/\Lambda_3 - \Delta_{EW}$ planes. The color coding is the same as in Figure 1.

contribution to muon $g - 2$ but with the wrong sign. This explains why we cannot provide resolution of the muon $g - 2$ anomaly from SUSY contributions in our scenario.

The latest (7.84) version of ISAJET [26] calculates the fine-tuning conditions related to the little hierarchy problem at M_{EW} . Including the one-loop effective potential contri-

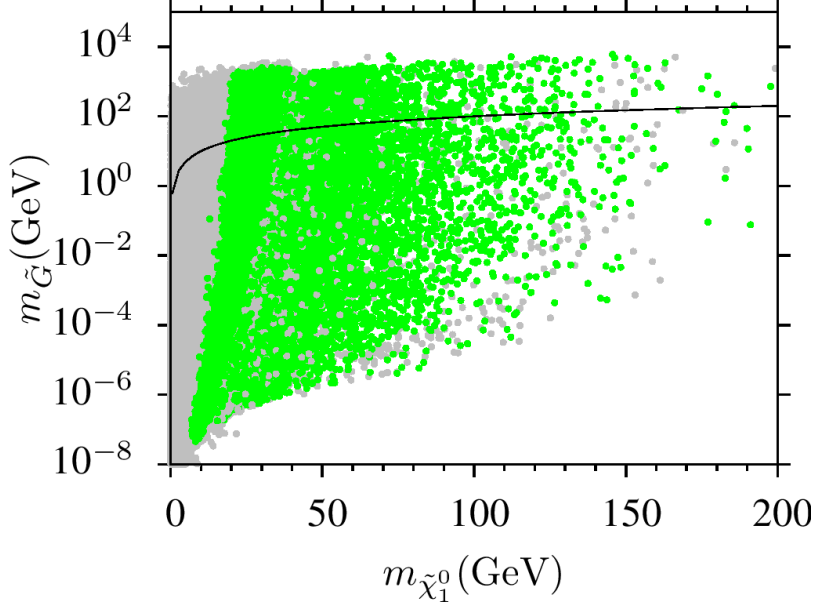


Figure 4: Gravitino and neutralino masses in the $m_{\tilde{G}} - m_{\tilde{\chi}_1^0}$ plane. The color coding is the same as in Figure 1. The solid line indicates regions where $m_{\tilde{G}} = m_{\tilde{\chi}_1^0}$.

contributions to the tree level MSSM Higgs potential, the Z boson mass is given by the relation:

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2. \quad (7)$$

The Σ 's stand for the contributions arising from the one-loop effective potential (for more details see ref. [20]). All parameters in Eq. (7) are defined at the weak scale M_{EW} .

In order to measure the EW scale fine-tuning condition associated with the little hierarchy problem, the following definitions are used [20]:

$$C_{H_d} \equiv |m_{H_d}^2/(\tan^2 \beta - 1)|, \quad C_{H_u} \equiv |-m_{H_u}^2 \tan^2 \beta/(\tan^2 \beta - 1)|, \quad C_\mu \equiv |-\mu^2|, \quad (8)$$

with each $C_{\Sigma_{u,d}^{u,d(i)}}$ less than some characteristic value of order M_Z^2 . Here, i labels the SM and supersymmetric particles that contribute to the one-loop Higgs potential. For the fine-tuning condition we have

$$\Delta_{EW} \equiv \max(C_i)/(M_Z^2/2). \quad (9)$$

Note that Eq. (9) defines the fine-tuning condition at M_{EW} without addressing the question of the origin of the parameters that are involved. Hence, Δ_{EW} represents a lower bound on fine-tuning [21].

As mentioned earlier, the little hierarchy problem can be ameliorated in our model, since M_3 and M_2 are generated by the two free parameters Λ_8 and Λ_3 respectively. It can be quantified with Δ_{EW} as shown in Figure 3 with plots in the $M_{Mess} - \Delta_{EW}$ and $\Lambda_8/\Lambda_3 - \Delta_{EW}$ planes. The color coding is the same as Figure 1. Acceptable fine-tuning is usually assumed when $\Delta_{EW} \leq 10^2$, and our model can yield $\Delta_{EW} \sim 30$ or so. As seen from the $M_{Mess} - \Delta_{EW}$ plane, it is possible to have solutions with $\Delta_{EW} \leq 100$ even for high values of $M_{Mess} < 10^{10}$ GeV. It is interesting to note that the solution with relatively

small Δ_{EW} appears with $0.1 < \Lambda_8/\Lambda_3 < 0.5$, which is a clear indication of the necessity of non-universal gauginos in the spectrum. A similar observation in gravity mediation scenario was made sometime ago in ref. [17].

Figure 4 presents results for the gravitino and neutralino masses in the $m_{\tilde{G}} - m_{\tilde{\chi}_1^0}$ plane. The color coding is the same as Figure 1. The solid line indicates regions where $m_{\tilde{G}} = m_{\tilde{\chi}_1^0}$. The LSP in gauge mediation models is usually the gravitino since its mass is expected to be much smaller than the typical sparticle mass. In our model the gravitino mass varies in a wide range from eV to TeV scales, and it is found to be the LSP over most of the parameter space. In standard scenarios, the WMAP (and Planck) bound on the LSP relic density ($\Omega h^2 \simeq 0.11$ [40]) yields gravitino mass ~ 200 eV, which makes the gravitino a candidate for hot dark matter. However, the latter cannot contribute more than 15% to the dark matter density and this, in turn, requires the gravitino mass to be less than 30 eV [41]. In this context, the gravitino can manifest itself through missing energy in colliders. In order to have a complete dark matter scenario one could invoke axions as cold dark matter in this region.

A gravitino mass $\gtrsim 30$ eV requires non-standard scenarios in order to agree with observations. Such non-standard scenarios include gravitino decoupling and freezing out earlier than in the standard scenario, which may be possible in a theory with more degrees of freedom than the MSSM [43]. A gravitino of mass \gtrsim keV is still possible and it can be cold enough to constitute all of the dark matter if non-standard scenarios, such as early decoupling, is assumed.

Finally we display three benchmark points which exemplify our findings, with all masses in GeV units. Point 1 exemplifies a solution with a LSP neutralino with a mass of about 80 GeV, even though the other sparticles are rather heavy. This point shows that regions of the parameter space which yield LSP neutralino, can be realized for a high $M_{\text{Mess}} \sim 10^{15}$ GeV, and require rather high fine-tuning ($\Delta_{EW} \sim 7600$). Point 2 represents a solution with a LSP gravitino with mass \sim keV scale. Such solutions can be obtained for low M_{Mess} values ($\sim 10^7$ GeV) with moderate to low fine-tuning. Similarly, Point 3 displays a solution with LSP gravitino of mass ~ 27 eV. The messenger scale and the required fine-tuning are low, similar to Point 2. The solutions exemplified by Point 3 offer gravitino as a plausible hot dark matter candidate.

5 Conclusion

We have explored the spectroscopy and related topics in a class of models within the framework of gauge mediation supersymmetry breaking where the messenger fields transform in the adjoint representation of the Standard Model gauge symmetry. To avoid “massless” or too light right-handed sleptons a non zero $U(1)_{B-L}$ D-term is introduced. This provides additional contributions to the soft supersymmetry breaking mass terms and makes the right-handed slepton masses compatible with the current experimental data. In this framework we show that the observed 125 GeV Higgs boson mass and the desired relic dark matter abundance can be simultaneously accommodated with relatively light sleptons accessible at the LHC. In the spectrum we do have relatively light smuons but due to the negative sign of bino mass at low scale the supersymmetric contribution either comes with the wrong sign or is not significant enough to explain the muon $g - 2$ anomaly.

	Point 1	Point 2	Point 3
Λ_3	0.12×10^4	0.49×10^6	0.61×10^5
Λ_8	0.15×10^7	0.14×10^6	0.28×10^6
M_{mess}	0.52×10^{16}	0.22×10^7	0.54×10^6
$\tan \beta$	54.4	34.9	57.2
D	1455	1578	1914
μ	6012	487	3086
Δ_{EW}	2920	54	1946
m_h	125.4	124.5	124.4
m_H	6003	1935	1867
m_A	5992	1923	1855
m_{H^\pm}	6004	1937	1869
$m_{\tilde{\chi}_{1,2}^0}$	81.9 , 223	5.01, 480	6.1, 329
$m_{\tilde{\chi}_{3,4}^0}$	5113, 5113	482, 2593	2796, 2796
$m_{\tilde{\chi}_{1,2}^\pm}$	223, 5365	493, 2552	330, 2757
$m_{\tilde{g}}$	9418	3115	5745
$m_{\tilde{u}_{L,R}}$	8324, 8361	4058, 5450	7719, 5576
$m_{\tilde{t}_{1,2}}$	5017, 5128	3679, 5038	5159, 7343
$m_{\tilde{d}_{L,R}}$	8322, 8334	4059, 3303	5598, 5576
$m_{\tilde{b}_{1,2}}$	7119, 7240	3213, 3747	5251, 5470
$m_{\tilde{\nu}_{e,\mu}}$	3886	5270	5708
$m_{\tilde{\nu}_\tau}$	3714	5217	5594
$m_{\tilde{\mu}_{L,R}}$	1942, 2809	5272, 4871	5863, 5607
$m_{\tilde{\tau}_{1,2}}$	1652, 2202	4753, 5213	5547, 5633
$m_{\tilde{G}}$	1833	2.7×10^{-7}	36×10^{-9}

Table 2: Benchmark points for exemplifying our results. All masses are in GeV. Point 1 exemplifies a solution for neutralino LSP. Point 2 depicts a solution with a low Δ_{EW} . Finally, Point 3 represents gravitino as hot dark matter solution.

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References

- [1] M. Dine and A. E. Nelson, Phys. Rev. D **48**, 1277 (1993); M. Dine, A. E. Nelson and Y. Shirman, Phys. Rev. D **51**, 1362 (1995); M. Dine, A. E. Nelson, Y. Nir and Y. Shirman, Phys. Rev. D **53**, 2658 (1996).
- [2] For a review, see G. F. Giudice and R. Rattazzi, Phys. Rept. **322**, 419 (1999).
- [3] P. Meade, N. Seiberg and D. Shih, Prog. Theor. Phys. Suppl. **177**, 143 (2009); M. Buican, P. Meade, N. Seiberg and D. Shih, JHEP **0903**, 016 (2009).
- [4] See, for instance, Z. Komargodski and N. Seiberg, JHEP **0903**, 072 (2009); Z. Kang, T. Li, T. Liu and J. M. Yang, JHEP **1204**, 016 (2012).
- [5] P. Draper, P. Meade, M. Reece and D. Shih, Phys. Rev. D **85**, 095007 (2012); M. A. Ajaib, I. Gogoladze, F. Nasir and Q. Shafi, Phys. Lett. B **713**, 462 (2012).
- [6] I. Gogoladze, A. Mustafayev, Q. Shafi and C. S. Un, Phys. Rev. D **91**, no. 9, 096005 (2015).
- [7] T. Han, T. Yanagida and R. J. Zhang, Phys. Rev. D **58**, 095011 (1998).
- [8] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014). doi:10.1088/1674-1137/38/9/090001
- [9] G. Bhattacharyya, B. Bhattacharjee, T. T. Yanagida and N. Yokozaki, Phys. Lett. B **725**, 339 (2013).
- [10] See for instance S. P. Martin, Adv. Ser. Direct. High Energy Phys. **21**, 1 (2010) and references therein.
- [11] G. Bhattacharyya, T. T. Yanagida and N. Yokozaki, Phys. Lett. B **749**, 82 (2015).
- [12] M. Drees, Phys. Lett. B **181**, 279 (1986).
- [13] C. F. Kolda and S. P. Martin, Phys. Rev. D **53**, 3871 (1996).
- [14] R. N. Mohapatra and R. E. Marshak, Phys. Rev. Lett. **44**, 1316 (1980) Erratum: [Phys. Rev. Lett. **44**, 1643 (1980)].
- [15] H. Georgi, in *Particles and Fields*, edited by C.E. Carlson, (A.I.P., New York, 1975); H. Fritzsch and P. Minkowski, Ann. Phys. **93**(1975)193.
- [16] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974).
- [17] H. Abe, T. Kobayashi and Y. Omura, Phys. Rev. D **76**, 015002 (2007); I. Gogoladze, M. U. Rehman and Q. Shafi, Phys. Rev. D **80**, 105002 (2009); D. Horton and G. G. Ross, Nucl. Phys. B **830** (2010) 221; S. Antusch, L. Calibbi, V. Maurer, M. Monaco and M. Spinrath, JHEP **1301** (2013) 187; I. Gogoladze, F. Nasir and Q. Shafi, Int. J. Mod. Phys. A **28**, 1350046 (2013); I. Gogoladze, F. Nasir and Q. Shafi, JHEP **1311**, 173 (2013); A. Kaminska, G. G. Ross and K. Schmidt-Hoberg, JHEP **1311**, 209 (2013); S. P. Martin, Phys. Rev. D **89** (2014) 3, 035011; K. Kowalska, L. Roszkowski, E. M. Sessolo and S. Trojanowski, JHEP **1404** (2014) 166.

- [18] A. H. Chamseddine, R. L. Arnowitt and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); R. Barbieri, S. Ferrara, and C. A. Savoy, Phys. Lett. B **119**, 343 (1982); L. J. Hall, J. D. Lykken, and S. Weinberg, Phys. Rev. D **27**, 2359 (1983); E. Cremmer, P. Fayet, and L. Girardello, Phys. Lett. B **122**, 41 (1983); N. Ohta, Prog. Theor. Phys. **70**, 542 (1983).
- [19] F. Brummer and W. Buchmuller, JHEP **1205** (2012) 006; F. Brammer, M. Ibe and T. T. Yanagida, Phys. Lett. B **726** (2013) 364; G. Bhattacharyya, T. T. Yanagida and N. Yokozaki, Phys. Lett. B **749** (2015) 82; H. Fukuda, H. Murayama, T. T. Yanagida and N. Yokozaki, Phys. Rev. D **92** (2015) no.5, 055032; L. Calibbi, T. Li, A. Mustafayev and S. Raza, Phys. Rev. D **93**, no. 11, 115018 (2016).
- [20] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, Phys. Rev. D **87**, no. 3, 035017 (2013).
- [21] A. Mustafayev and X. Tata, Indian J. Phys. **88**, 991 (2014) [arXiv:1404.1386 [hep-ph]].
- [22] Y. Yamada, Phys. Rev. Lett. **72**, 25 (1994); S. P. Martin and M. T. Vaughn, Phys. Rev. D **50**, 2282 (1994), Erratum: [Phys. Rev. D **78**, 039903 (2008)].
- [23] I. Gogoladze, Q. Shafi and C. S. Ün, Phys. Rev. D **92**, no. 11, 115014 (2015).
- [24] A. Albaid and K. S. Babu, Phys. Rev. D **88**, 055007 (2013); J. A. Evans, D. Shih and A. Thalapillil, JHEP **1507**, 040 (2015).
- [25] C. Bachas, C. Fabre and T. Yanagida, Phys. Lett. B **370**, 49 (1996); J. L. Chkareuli and I. G. Gogoladze, Phys. Rev. D **58**, 055011 (1998); B. Bajc, P. Fileviez Perez and G. Senjanovic, Phys. Rev. D **66**, 075005 (2002).
- [26] F. E. Paige, S. D. Protopopescu, H. Baer and X. Tata, hep-ph/0312045.
- [27] D. M. Pierce, J. A. Bagger, K. T. Matchev, and R.-j. Zhang, Nucl. Phys. **B491**, 3 (1997).
- [28] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, JHEP **1106**, 117 (2011).
- [29] G. Belanger, F. Boudjema, A. Pukhov and R. K. Singh, JHEP **0911**, 026 (2009); H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP **0803**, 056 (2008).
- [30] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].
- [31] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].
- [32] The ATLAS collaboration, ATLAS-CONF-2015-067.
- [33] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **110**, 021801 (2013).
- [34] Y. Amhis *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].

- [35] D. Asner *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:1010.1589 [hep-ex].
- [36] Muon g-2 Collaboration, Phys. Rev. D **73**, 072003 (2006).
- [37] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).
- [38] G. Hinshaw *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **208**, 19 (2013).
- [39] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D **71**, 063534 (2005); J. L. Feng, M. Kamionkowski and S. K. Lee, Phys. Rev. D **82**, 015012 (2010).
- [40] G. Hinshaw *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **208**, 19 (2013).
- [41] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D **71**, 063534 (2005).
- [42] I. Gogoladze, F. Nasir and Q. Shafi, Int. J. Mod. Phys. A **28**, 1350046 (2013) doi:10.1142/S0217751X13500462 [arXiv:1212.2593 [hep-ph]].
- [43] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D **71**, 063534 (2005); J. L. Feng, M. Kamionkowski and S. K. Lee, Phys. Rev. D **82**, 015012 (2010).